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Breakdown phenomenon study in the bidirectional pedestrian flow

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Abstract

Pedestrian dynamics has been being a popular research area. In this paper, breakdown probability in the bidirectional flow that includes pedestrians with heterogeneities is investigated. Reaction time appears to have the most pronounced breakdown probability, followed by desired velocity and then body size. The relationship between the start time of breakdown and inflow reflects the decreasing trend of the start time of breakdown with increasing inflow. Furthermore, the smaller the value of the start time of breakdown for the same inflow, the larger the effect of the heterogeneity in a parameter of the social force model on breakdown by cross-comparisons.

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1. Introduction

In reality, different pedestrians have different walking characteristics and physical factors, which means the pedestrian flows are always heterogeneous. Some people may prefer to walk faster because of their habits, weather or personal reasons, some people may walk slower as a result of gender, age or disability. Apparently, all these different preferences directly result in a change of walking velocity. Therefore, studying heterogeneity of pedestrians' different preferences that may affect pedestrians' velocity is meaningful to better comprehend pedestrian flow phenomena.

In recent years, continuous improvement in modeling methods of pedestrians has been made. Generally, pedestrian models fall into three categories: macroscopic, mesoscopic and microscopic models. Some good overviews about pedestrian models are given by Zheng et al. (2009); Duives et al. (2013). Dynamic features, such as lane formation in the bidirectional flow, the clogging effect, herding and the zipper effect, have been observed during experiments or have been represented using pedestrian models. Bidirectional flow as a type of pedestrian flow has attracted much attention of scientists because of its various dynamic movement features. Helbing et al. (2002) proposed that pedestrians in the bidirectional flow spontaneously organized in lanes with uniform walking direction if the density

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of pedestrians was high enough. According to Tian et al. (2009), there were three phases in the bidirectional flow: the freely moving phase, the coexisting phase and the uniformly congested phase. Yu and Song (2007) proposed that phase transition from free moving to jamming occurred with the increase of entrance density in the bidirectional flow. Furthermore, Campanella et al. (2009) preliminary investigated the effects of heterogeneity on breakdown probability. Based on the above investigations, we will conduct a further research on breakdown phenomenon of bidirectional pedestrian flow in this paper. The most important work is around the relationship between the start time of breakdown and inflow for pedestrians with heterogeneities by analyzing the statistical simulation results.

In this paper, the social force model proposed by Helbing et al. (2000) is considered as the reference model to study the effects of heterogeneity in different parameters of the social force model on the breakdown phenomenon of the bidirectional flow. One reason is that the social force model as a microscopic model puts particular emphasis on the mutual influence of individuals in a continuous space by defining some forces, where detailed behaviors could be considered making the simulated pedestrians more realistic. Another reason is that it has been shown to qualitatively regenerate some self-organization behaviors like lane formation.

The rest structure of this paper is as follows. The social force model is presented in section 2. Section 3 studies the effect of heterogeneity in different parameters of the social force model on breakdown phenomenon of bidirectional pedestrian flow, and also cross-compares some simulation results. The paper ends with conclusions and an overview of future research.

2. Description of the social force model

In the social force model, pedestrians are driven by three forces: the desired force, $\vec{f}_i^0$; the interaction force between pedestrians i and j, $\vec{f}_{ij}$; and the interaction force between pedestrian i and walls w, $\vec{f}_{iw}$. The motion equation for each pedestrian i based on Newton's second law of motion is

$$m_i \frac{d\vec{v}_i(t)}{dt} = \vec{f}_i^0 + \sum_{j(\neq i)} \vec{f}_{ij} + \sum_{w} \vec{f}_{iw}, \tag{1}$$

where m_i is the mass of pedestrian i, and $\vec{v}_i(t)$ is the actual walking velocity.

The desired force, $\vec{f}_i^0$, directing the pedestrian to its destination, can be expressed by

$$\vec{f}_i^0 = m_i \frac{v_i^0(t)\,\vec{e}_i^{\,0} - \vec{v}_i(t)}{\tau_i}, \tag{2}$$

where v_i^0 is the value of the desired speed, $\vec{e}_i^{\,0}$ is the desired walking direction, and τ_i is the adaptation time.

The interaction force between pedestrians i and j, $\vec{f}_{ij}$, contains the socio-psychological force, $\vec{f}_{ij}^s$, and the physical force, $\vec{f}_{ij}^p$. The socio-psychological force reflects pedestrians' psychological tendency to steer away from each other. The physical force occurs when there is physical contact and thus pedestrians are not free to move. In other words, the physical force is valid only when the distance between two pedestrian centers, d_{ij}, is less than the sum of the radii of these two pedestrians, $r_{ij} = r_i + r_j$. The physical force contains "body force", $\vec{f}_{ij}^{p_1}$, to counteract the body compression, and "sliding friction force", $\vec{f}_{ij}^{p_2}$, to hinder the relative tangential motion. The corresponding expression has the following form:

$$\vec{f}_{ij} = \vec{f}_{ij}^s + \vec{f}_{ij}^p, \tag{3}$$

where

$$\vec{f}_{ij}^s = A_i \exp\left[\left(r_{ij} - d_{ij}\right)/B_i\right]\vec{n}_{ij}, \tag{4}$$

$$\vec{f}_{ij}^p = \vec{f}_{ij}^{p_1} + \vec{f}_{ij}^{p_2} = kg\left(r_{ij} - d_{ij}\right)\vec{n}_{ij} + \kappa g\left(r_{ij} - d_{ij}\right)\triangle v_{ji}^t \vec{t}_{ij}. \tag{5}$$

Here, A_i, B_i, k, κ are parameters. $\vec{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\vec{r}_i - \vec{r}_j)/d_{ij}$ is the unit vector pointing from pedestrian j to pedestrian i, where $\vec{r}_i$ and $\vec{r}_j$ are the positions of pedestrians i and j respectively. $\vec{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ is the tangential

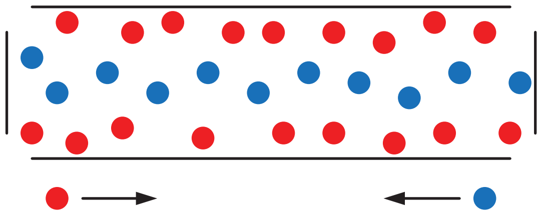

Fig. 1. The diagram of the simulation scenario for the bidirectional flow.

direction, and $\triangle v^t_{ji} = \left(\vec{v}_j - \vec{v}_i\right) \cdot \vec{t}_{ij}$ is the velocity difference along the tangential direction. The function $g(x)$ is zero if the pedestrians do not touch each other ($d_{ij} > r_{ij}$), otherwise is equal to the argument x.

The interaction force between pedestrian i and walls w, $\vec{f}_{iw}$, is treated analogously, thus is similar to equation (3) and is defined by

$$\vec{f}_{iw} = A_i \exp[(r_i - d_{iw})/B_i]\vec{n}_{iw} + kg(r_i - d_{iw})\vec{n}_{iw} + \kappa g(r_i - d_{iw}) \triangle v^t_{wi}\vec{t}_{iw}. \tag{6}$$

Here, d_{iw} is the distance between the center of pedestrian i and the surface of the closest boundary of the wall.

Helbing et al. (2000) specified the parameters in the social force model as follows : $m = 80kg, A = 2000N, B = 0.08m, \kappa = 240000kg \cdot m^{-1} \cdot s^{-1}, k = 120000kg \cdot s^{-2}$.

3. Heterogeneity study for breakdown phenomenon of the bidirectional Flow

In this section, we will first give the setup of the simulation scenarios directing at the bidirectional flow with heterogeneity, then we will show the effect of heterogeneities in desired velocity, reaction time and body size of the social force model on the breakdown phenomenon.

3.1. Simulation scenario setup

As Fig. 1 shows, the size of the corridor is $10m * 4m$, and the inflows of pedestrians on both sides are from outside of the corridor. In order to create congestions, this inflow is controlled, and specific demand patterns to cause a breakdown will be identified. In the actual bidirectional flow, each pedestrian has his or her own personality such as physical condition, age and body size. In our simulations, the heterogeneities in reaction time, desired velocity, and body size of the social force model which could reflect the personalities of pedestrians are investigated to obtain their effects over the breakdown dynamics of the bidirectional flow. The different scenarios are shown in Table 1. Here, pedestrians' reaction time τ is uniformly distributed between the minimum value $0.15s$ and the maximum value $0.50s$, whose deviations σ_τ are $0.00, 0.05, 0.10$ standing for the reaction time with small, medium and large heterogeneities respectively. Radius r is uniformly distributed between $0.250m$ and $0.300m$ whose deviations σ_r are $0.000, 0.025, 0.050$ standing for radius with small, medium and large heterogeneities respectively. Pedestrians' desired velocity, however, meets normal distribution whose mean is $1.45m/s$ and standard deviation σ_v are $0.0, 0.2, 0.4$ standing for the desired velocity with small, medium and large heterogeneities respectively.

In each scenario, the inflow value is constant during a simulation which lasts $1200s$ even though the breakdown happens, and the inflow pattern is similar for all scenarios. The corresponding results are the values after doing 100 times simulations. In our simulation, we set that the minimum inflow is $1p/s$ and the maximum inflow is $2p/s$. It should be noted that $1200s$ for each simulation is long enough for the bidirectional flow study because the length of corridor in our simulation is only $10m$, and a pedestrian only needs about $10s$ to go through the corridor. Corresponding to Campanella et al. (2009) where the corridor size is the same with our setting, total breakdown is defined as there are at least 60 pedestrians who would walk very slowly in five consecutive seconds. Here, we assume this slow velocity has a maximum value of $0.3m/s$.

Table 1. Parameter settings in different simulation scenarios Campanella et al. (2009).

Simulation Scenario[a]	Reaction time $\tau(s)$	Deviation σ_τ	Desired Speed $v^0(m/s)$	Standard deviation σ_v	Radius $r(m)$	Deviation σ_r
0: Reference scenario	0.15	0.00	1.45	0.2	0.250	0.050
1: With large desired speed heterogeneity				0.4		
2: With no desired speed heterogeneity				0.0		
3: With large reaction time heterogeneity		0.10				
4: With medium reaction time heterogeneity		0.05				
5: With medium body size heterogeneity						0.025
6: With no body size heterogeneity						0.000

[a] In scenarios 1-6, only one parameter replaces the corresponding parameter in the reference scenario, others keep the same.

3.2. Analysis of breakdown phenomenon

We first want to know whether or not the breakdown probability has a certain relationship with inflow. Secondly, effects of heterogeneities in different parameters of the social force model are investigated for the breakdown phenomenon. Fig. 2 shows a rough trend that breakdown probability increases with increasing inflow until breakdown probability approaches to 1. The large heterogeneity in reaction time has a similar effect on breakdown probability to the medium heterogeneity in reaction time, and both of them have the largest influence on breakdown probability. Besides, large heterogeneity in desired velocity also has a significant effect on breakdown probability though not as much as that of reaction time. Heterogeneity in body size has the least effect on breakdown probability compared with the two other parameters in the social force model. It should be noted that the reference scenario is set as pedestrians' body size is with large heterogeneity, desired speed is with medium heterogeneity, and short reaction time with no heterogeneity in this paper in order to reflect the anisotropy, which is the same as in Campanella et al. (2009).

In order to have a deeper understanding of the breakdown phenomenon, the distribution of the start time of breakdown in the course of inflow for the above different scenarios is investigated and analyzed. Fig. 3, Fig. 4 and Fig. 5 respectively show the box-plots of the relationship between inflow and the start time of breakdown for pedestrians with large, medium and small heterogeneities in desired velocity. It is very clear that the start time of breakdown decreases with increasing inflow in each scenario of the heterogeneity in desired velocity, which indicates breakdown is easier to occur in the case of high inflow for the same pattern of pedestrian flow. Besides, we can find that the start time of breakdown is with less variation when inflow is relatively high, thus it is easier to predict this start time. Moreover, by comparing these three figures, we can summarize that in the case of the same inflow in Fig. 3, Fig. 4 and Fig. 5, the smaller the value of the start time of breakdown, the larger the effect of correspond heterogeneity in the desired velocity of the social force model.

Fig. 6, Fig. 7 and Fig. 4 respectively depict the box-plots of the relationship between inflow and the start time of breakdown for pedestrians with large, medium and small heterogeneities in the reaction time. it can be observed that medium heterogeneity in the reaction time nearly has the same effect as large heterogeneity in reaction time over the start time of breakdown. By comparing Fig. 6 and Fig. 3, it is very distinct that the mean value of the start time of breakdown in Fig. 3 decreases more moderately with increasing inflow, and is higher than that in Fig. 6 in the case of the same inflow, which reflects that the heterogeneity in reaction time is more pronounced to breakdown phenomenon than the heterogeneity in desired velocity.

Fig. 4, Fig. 8 and Fig. 9 respectively depict the box-plots of the relationship between inflow and the start time of breakdown for pedestrians with large, medium and small heterogeneities in body size. The most obvious phenomenon is that breakdown phenomenon only occurs when inflow is relatively high, which means the effect of heterogeneity in body size is not as pronounced as that in desired velocity or in reaction time.

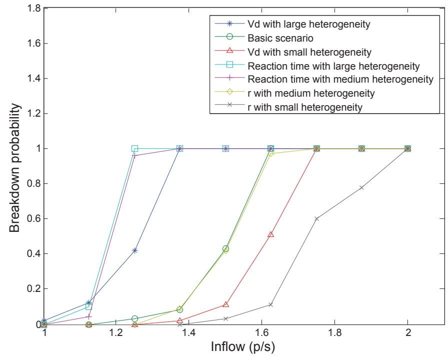

Fig. 2. The breakdown probability versus inflow of pedestrians.

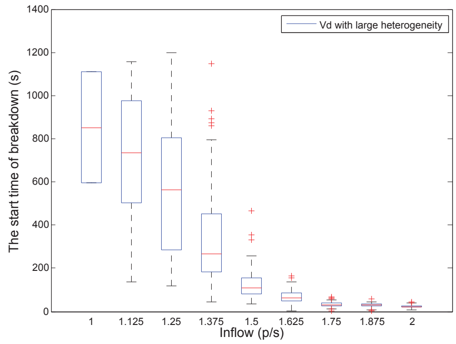

Fig. 3. Box-plot for pedestrians with large heterogeneity in desired velocity.

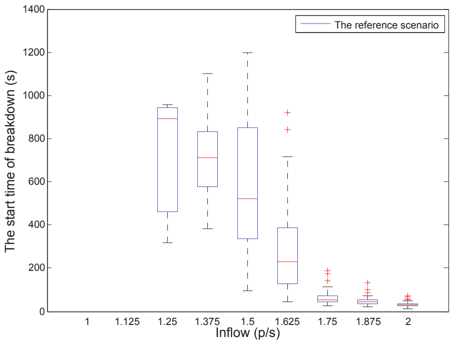

Fig. 4. Box-plot for the reference scenario.

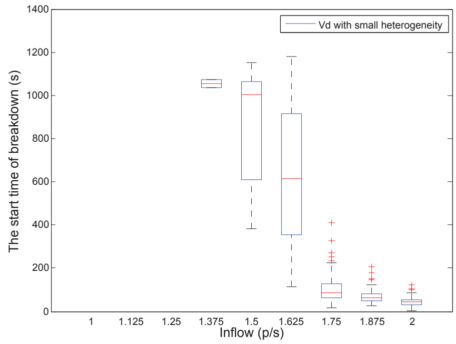

Fig. 5. Box-plot for pedestrians with small heterogeneity in desired velocity.

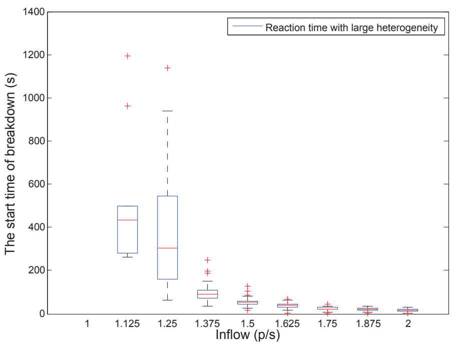

Fig. 6. Box-plot for pedestrians with large heterogeneity in reaction time.

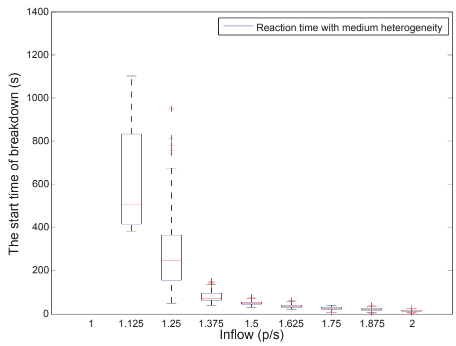

Fig. 7. Box-plot for pedestrians with medium heterogeneity in reaction time.

4. Conclusion

The effect of heterogeneity in three parameters of the social force model, namely desired velocity, reaction time and body size, on breakdown probability of the bidirectional flow is investigated in this paper, showing that heterogeneity in reaction time is the most pronounced to breakdown probability, followed by that in desired velocity, and then in body size. The relationship between the start time of breakdown and inflow of pedestrians is also studied, which indicates the decreasing trend of the start time of breakdown with increasing inflow, and it is easier to happen breakdown in the

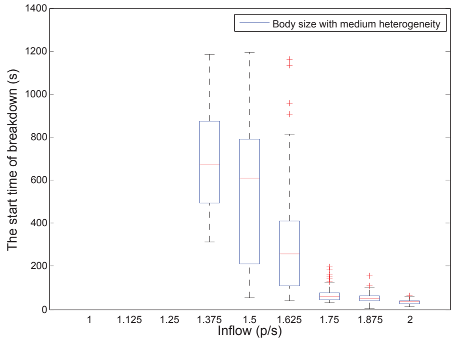

Fig. 8. Box-plot for pedestrians with medium heterogeneity in body size.

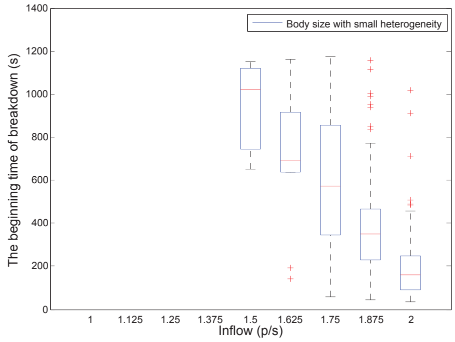

Fig. 9. Box-plot for pedestrians with small heterogeneity in body size.

case of high inflow. Moreover, cross-comparison is carried out, from which we can conclude that the larger effect on breakdown phenomenon will be performed on pedestrian flow, if the value of the start time of breakdown is smaller in different simulation scenarios under the same inflow. Whether or not the size of the corridor has the influence on the start time of breakdown under the same inflow can be done in the future work, and also the measures to reduce the occurrence of breakdown can be done. In the practical application, the simulation results about breakdown in this paper can be used as the guidance for the design of corridor of public places according to the inflow information.

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